

SPIN EVOLUTION OF ACCRETING YOUNG STARS. II. EFFECT OF ACCRETION-POWERED STELLAR WINDS

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ABSTRACT

We present a model for the rotational evolution of a young, solar-mass star interacting magnetically with an accretion disk. As in a previous paper (Paper I), the model includes changes in the star's mass and radius as it descends the Hayashi track, a decreasing accretion rate, and a prescription for the angular momentum transfer between the star and disk. Paper I concluded that, for the relatively strong magnetic coupling expected in real systems, additional processes are necessary to explain the existence of slowly rotating pre-main-sequence stars. In the present paper, we extend the stellar spin model to include the effect of a spin-down torque that arises from an accretion-powered stellar wind. For a range of magnetic field strengths, accretion rates, initial spin rates, and mass outflow rates, the modeled stars exhibit rotation periods within the range of 1–10 days in the age range of 1–3 Myr. This range coincides with the bulk of the observed rotation periods, with the slow rotators corresponding to stars with the lowest accretion rates, strongest magnetic fields, and/or highest stellar wind mass outflow rates. We also make a direct, quantitative comparison between the accretion-powered stellar wind scenario and the two types of disk-locking models (namely the X-wind and Ghosh & Lamb type models) and identify some remaining theoretical issues for understanding young star spins.

Subject headings: Accretion, accretion disks, Stars: evolution, Stars: magnetic field, Stars: pre-main-sequence, Stars: rotation, Stars: winds, outflows

1. INTRODUCTION

There remain a number of unexplained phenomena related to the spin rates of young, low mass ($\lesssim 2M_{\odot}$) stars (e.g., Herbst et al. 2007; Scholz 2009; Irwin & Bouvier 2009). At the youngest stages, the fundamental dilemma is that a large fraction of stars rotate more slowly than expected, given that the stars are in the process of contracting and are often accreting material with high specific angular momentum (i.e., from a circumstellar disk). In the absence of significant spin-down torques, one would expect these stars to spin near breakup speed. However, observations reveal that approximately half of solar mass stars with ages of less than a few million years rotate at less than $\sim 10\%$ of their breakup velocities (e.g., Rebull et al. 2004; Herbst et al. 2007; Scholz 2009). Thus, for a large fraction of pre-main-sequence stars, there exists some mechanism that removes significant amounts of angular momentum.

In a previous paper (Matt et al. 2010, hereafter Paper I), we examined whether the magnetic connection between a young star and surrounding accretion disk can be solely responsible for the angular momentum loss. That work employed a model similar to some previous studies in the literature (Cameron & Campbell 1993; Yi 1994, 1995; Cameron et al. 1995; Armitage & Clarke 1996), which computes the time-evolution of the mass, radius, and rotation rate of an accreting star. Specifically, Paper I presented calculations of the spin rate of a one-solar-mass star as it evolves from an age of 30,000 yr to 3 Myr. The calculations considered the contraction of the star during the Hayashi (1961) phase and an ex-

ponentially decreasing accretion rate. The calculations also considered a range of initial accretion rates, spin rates, and magnetic field strengths, approximately representative of typical observed or expected values for low mass pre-main-sequence stars. Rather than attempt to explain all phenomena related to young star spins, the primary goal in Paper I (and in the present paper) was to address the fundamental question of whether the models could produce spin rates within the observed typical range of ~ 1 –10 days.

The main difference with previous works is that the model in Paper I used the magnetic torque formulation presented by Matt & Pudritz (2005b), which includes the effects of the magnetic coupling (diffusivity) in the disk and the loss of magnetic connection that occurs when field lines are sufficiently twisted azimuthally (e.g., Uzdensky et al. 2002). When considering the strong magnetic coupling (i.e., low diffusivity or high magnetic Reynolds number) expected in real systems, Paper I concluded that the spin-down torques arising from the star-disk interaction alone were not sufficient to produce rotation periods longer than ~ 3 days at ages of 1–3 Myr. The main result of Paper I suggests that additional spin-down torques are necessary to explain the slow rotators. That model neglected any torques that may arise along open field regions, such as torques from stellar winds, so a natural next step is to consider whether or under which circumstances such torques may be important.

Powerful and large-scale jets and outflows are observed to emanate from accreting young stars with outflow rates of the order of 0.01–0.1 times the accretion

rates (e.g., Reipurth & Bally 2001; Cabrit 2007). Stellar winds—that is, outflows that are magnetically connected to the star, as opposed to the accretion disk—may be an important component in these large-scale flows (e.g., Decampli 1981; Kwan & Tademaru 1988; Fendt et al. 1995; Fendt & Camenzind 1996; Paatz & Camenzind 1996; Hirose et al. 1997; Fendt & Elstner 2000; Bogovalov & Tsinganos 2001; Sauty et al. 2002, 2004; Meliani et al. 2006; Matsakos et al. 2008, 2009; Fendt 2009; Romanova et al. 2009; Sauty et al. 2011). Furthermore, high-resolution spectroscopic observations of these systems show some emission line features that appear to be best explained by the presence of stellar winds, and that these signatures generally correlate with the accretion rates (e.g., Hartmann et al. 1982; Kwan & Tademaru 1988; Hartmann et al. 1990; Edwards et al. 2003; Dupree et al. 2005; Edwards et al. 2006; Kurosawa et al. 2006; Kwan et al. 2007; Johns-Krull & Herczeg 2007; Kurosawa et al. 2011). The idea that powerful stellar winds could also be the primary agent for removing angular momentum from the star has been suggested or explored by several authors (Hartmann & MacGregor 1982; Mestel 1984; Hartmann & Stauffer 1989; Tout & Pringle 1992; Paatz & Camenzind 1996; Hirose et al. 1997; Ferreira et al. 2000; Rekowski & Brandenburg 2004; Romanova et al. 2005; Matt & Pudritz 2005a; Rekowski & Brandenburg 2006; Matt & Pudritz 2008b; Romanova et al. 2009; Zanni & Ferreira 2009; Sauty et al. 2011). Matt & Pudritz (2005a, 2008b) showed that a stellar wind will be much more effective at spinning down a star than the magnetic connection between the star and disk, as long as the mass outflow rate is high enough. In order to maintain a sufficiently high mass loss rate, Matt & Pudritz (2005a) suggested that the stellar wind is somehow powered by the accretion process, and Matt & Pudritz (2008a) suggested that accretion onto the star may power a stellar wind by the excitation of a large flux of Alfvén waves along the open field lines. The idea of a wave-driven and accretion-powered stellar wind was further explored by Cranmer (2008, 2009).

In the present paper, we explore the role of stellar winds in the spin evolution of a young star that is also interacting magnetically with an accretion disk. The model (described in §2) is identical to that of Paper I except that the star experiences an additional torque from a stellar wind. This introduces only one new parameter, the mass outflow rate in the wind, which we take to be a fraction of the accretion rate, as expected for an accretion-powered stellar wind (hereafter, APSW). The results in section 3 demonstrate how an APSW, acting during the entire accretion history, may explain the typical range of observed spin rates. In section 4, we compare the present model with disk-locking models. A discussion of the conclusions of this work and remaining challenges are contained in section 5.

2. STELLAR SPIN EVOLUTION MODEL

In order to best compare the effects of powerful stellar winds to the torques arising in the star-disk magnetic interaction alone, we employ the same assumptions, equations, and method as Paper I, except that we have included the mass loss and torque resulting from the

wind. This section lists the relevant equations and points out where there are differences from Paper I (where the reader will also find more details).

2.1. Mass Flow

The mass accretion rate onto the stellar surface follows an exponential decay,

$$\dot{M}_a = \dot{M}_{a0} e^{-t/t_a}, \quad (1)$$

where \dot{M}_{a0} is the mass loss rate at $t = 0$, and t_a is the exponential decay timescale. Following Paper I, we adopt $t_a = 10^6$ yr, for all models, and two different values of \dot{M}_{a0} so that the models span a range of accretion rates. The two values correspond to a “low” accretion rate with $\dot{M}_{a0} = 10^{-8} M_\odot \text{ yr}^{-1}$ and a “high” accretion rate with $\dot{M}_{a0} = 10^{-7} M_\odot \text{ yr}^{-1}$ (see Fig. 1 of Paper I¹). In all cases, we chose an initial stellar mass, such that the mass of the star at the end of the computation (at an age of 3 Myr) equals one solar mass (see Fig. 2 of Paper I).

At the same time, the present work considers the additional effect of a stellar wind. The general picture of simultaneous inflow and outflow from the star is as follows. A fraction of the stellar magnetic flux connects to the accretion disk, which is responsible for the magnetic torques between the two and for channeling an accretion flow onto the star. The stellar wind flows from the polar regions of the star, where the magnetic field lines reach beyond the magnetosphere. This region of the magnetic field is susceptible to being opened and kept open by energetic processes, such as disk and/or stellar winds (e.g., Safier 1998; Matt & Pudritz 2005b) or differential rotation between the star and disk (e.g., Uzdensky et al. 2002). The basic idea behind APSWs is that a fraction of the accretion energy that is dissipated near the surface of the star ultimately powers a stellar wind. For this to work, energy deposited along the accreting field lines should transfer laterally (likely via waves) across the accretion flow and into the open field region. In the open field region, this energy then drives an enhanced stellar wind, where the outflowing mass is from the star and is distinct from the material that is currently accreting onto the star. A more detailed description of these processes are given in (e.g.) Matt & Pudritz (2005a) and Cranmer (2008), and an illustration of the model is given in Figure 1 of each of those works.

When the energy responsible for driving the wind ultimately comes from the accretion process, it stands to reason that the mass outflow rate \dot{M}_w will be ultimately tied to the accretion rate (Matt & Pudritz 2005b; Cranmer 2008, 2009). Thus, we parameterize the stellar wind outflow rate using

$$\chi \equiv \frac{\dot{M}_w}{\dot{M}_a}. \quad (2)$$

The evolution of the star’s mass is thus given by

$$\frac{dM_*}{dt} = (1 - \chi)\dot{M}_a. \quad (3)$$

¹ Paper I employed a different nomenclature, where $\dot{M}_{a0} \equiv M_D t_a^{-1}$, but regardless we adopt the same two values for the initial accretion rates as in Paper I.

Hartmann & Stauffer (1989) suggested that a value of $\chi \sim 0.1$ is necessary for the angular momentum outflow rate in a stellar wind to be comparable to the angular momentum deposited onto the star from accretion of disk material (and see Matt & Pudritz 2005b). Observations of large-scale outflows from T Tauri stars and (presumably younger) Class I sources indicate mass outflow rates of ~ 0.1 times the accretion rates, with about an order of magnitude of scatter and/or uncertainty in this value (e.g., see review by Cabrit 2007). It is still not clear what fraction of the mass outflow rates observed on large-scales may be due to flows that are magnetically connected to the star (as required in the present work), as opposed to flows from the accretion disk (e.g., Ferreira et al. 2006; Kurosawa et al. 2006; Kwan et al. 2007; Kurosawa et al. 2011). Recent models of accretion-powered stellar winds by Cranmer (2008, 2009) exhibit outflows from the star itself with $\chi \sim 0.01$. Thus, in the present work, we consider cases with both $\chi = 0.1$ and 0.01 , to explore a possible range of this value.

2.2. Stellar Structure and Evolution

The evolution of the stellar structure follows simple Kelvin-Helmholtz contraction of a polytrope (with index $3/2$). This treatment results in an evolution of stellar radius that follows

$$\frac{dR_*}{dt} = 2 \frac{R_*}{M_*} \dot{M}_a (1 - \chi) - \frac{28\pi\sigma R_*^4 T_e^4}{3GM_*^2}, \quad (4)$$

where R_* and M_* are the stellar radius and mass, T_e is the effective temperature of the star, and σ and G are the Stefan-Boltzmann constant and Newton's gravitational constant. As in Paper I, we adopt an initial stellar radius of $8R_\odot$ and constant photospheric temperature $T_e = 4280$ K for all calculations, so that the evolution of the star's structure resembles that from the model of Siess et al. (2000), as the star descends along the Hayashi track in the H-R diagram (see Fig. 3 in Paper I). The only difference between this equation and the corresponding equation of Paper I is the addition of the factor $(1 - \chi)$, which takes mass loss into account.

2.3. Spin Evolution

The evolution of the angular spin rate of the star follows

$$\frac{d\Omega_*}{dt} = \frac{T_*}{I_*} - \Omega_* \left(\frac{\dot{M}_a}{M_*} (1 - \chi) + \frac{2}{R_*} \frac{dR_*}{dt} \right), \quad (5)$$

where Ω_* is the (solid body) angular rotation rate of the star, T_* is the net torque on the star, and I_* is the stellar moment of inertia, $I_* \equiv k^2 M_* R_*^2$, where k is the normalized radius of gyration (we adopt $k^2 = 0.2$). The only difference between this equation and the corresponding equation of Paper I is the addition of the factor $(1 - \chi)$, which takes mass loss into account.

It is often instructive to express the spin rate as a fraction of the breakup speed, defined as the Keplerian velocity at the star's equator. This normalized spin rate is defined

$$f \equiv \Omega_* \sqrt{\frac{R_*^3}{GM_*}}. \quad (6)$$

Following Paper I, we consider two cases with different initial spin rates. The two cases have initial fractional spin rates of $f_0 = 0.3$ and 0.06 , representing the two extremes of rapid and slow initial rotation.

2.4. Torques on the Star

The present work considers the simultaneous effects of torques arising in the magnetic star-disk interaction and angular momentum loss from stellar winds. In both cases, the angular momentum gain and loss of the star is primarily transmitted by a magnetic field. The model assumes a rotation-axis-aligned dipole magnetic field, with a strength of B_* at the surface and equator of the star. We consider two different values of the magnetic field strength, $B_* = 500$ G and 2000 G, in addition to a case with $B_* = 0$ used for comparison. The model assumes that B_* is constant in time for all cases.

2.4.1. Magnetic Star-Disk Interaction Torques

The torques arising from the magnetic interaction between the star and accretion disk follow Matt & Pudritz (2005b), and the governing equations are given in Paper I. It is convenient to define the corotation radius

$$R_{co} \equiv \left(\frac{GM_*}{\Omega_*^2} \right)^{1/3} = f^{-2/3} R_*, \quad (7)$$

which is the singular radius in the Keplerian disk that rotates at the same angular speed as the star. This location is physically meaningful in the magnetic star-disk interaction because it is where the differential rotation between the star and disk equals zero.

The magnetic field of the star is typically strong enough to be able to truncate the disk at a distance of a few stellar radii. The truncation radius is denoted R_t . The torque associated with disk truncation and infall of material from R_t to the stellar surface is the accretion torque T_a . There is also a magnetic torque associated with the magnetic connection to a range of radii in the disk. This magnetic torque is denoted T_m . The method and equations used for calculating R_t , T_a , and T_m are given in Paper I and are not modified for the present work.

Two key parameters involved in the calculation of the star-disk interaction torques capture the physics of the magnetic coupling strength (parameter β) and the opening of magnetic field lines due to the differential rotation (parameter γ_c ; see Paper I and Matt & Pudritz 2005b). Parameter γ_c represents the maximum ratio between the azimuthal and vertical magnetic field components (B_ϕ/B_z) threading the disk, in order for the dipolar magnetic field lines to remain closed. In the present work, we adopt $\gamma_c = 1$ which corresponds to realistic expectations (Uzdensky et al. 2002). Parameter β is equivalent to the inverse of the magnetic Reynolds number in the inner disk region. Here we adopt $\beta = 0.01$, presented in Paper I (and Matt & Pudritz 2005b) as a reasonable guess for T Tauri systems. The effect of varying these two parameters was the subject of Paper I.

2.4.2. Stellar Wind Torque

In order to calculate the angular momentum loss via stellar winds, we use the stellar wind torque formulation

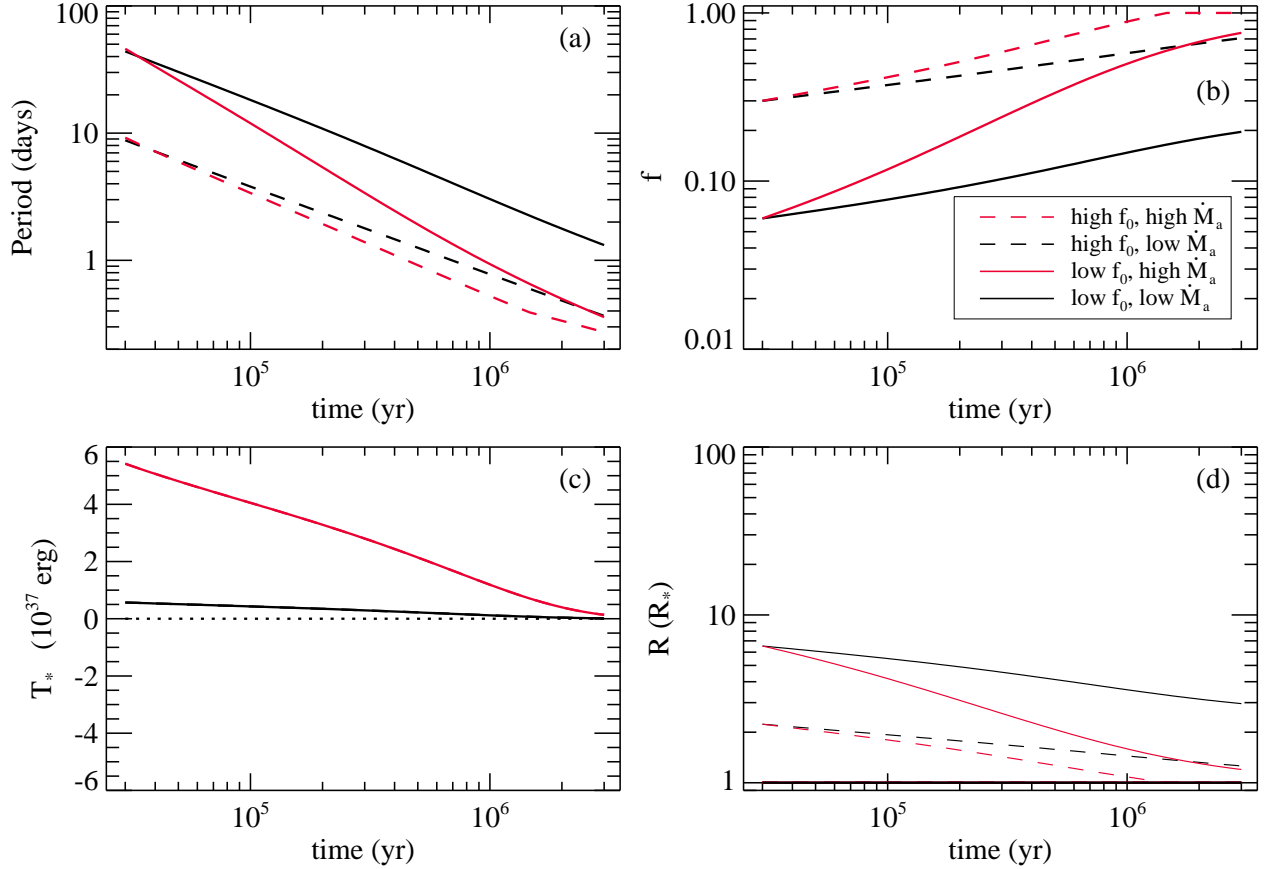


Figure 1. Time-evolution of various quantities for the $B_* = 0$ case. Panel (a) shows the rotation period in days, and panel (b) shows the spin rate expressed as a fraction of breakup speed. The four lines shown represent the two choices of accretion history and two initial spin rates. The red and black lines correspond to the high and low accretion rates, respectively. The solid and dashed lines correspond to models with an initial spin rate of 0.06 and 0.3 times the breakup rate, respectively. Panel (c) shows the net torque on the star (eq. [10]) for each case. In this panel, the dashed and solid lines of a given color lie on top of each other, since the spin rate does not affect the torque, when $B_* = 0$. The horizontal dotted line indicates $T_* = 0$ for clarity. Panel (d) shows the location of the truncation radius (R_t , thick lines) and the corotation radius (R_{co} , thin lines; eq. [7]), in units of the stellar radius. Here, $R_t = R_*$ for all models, since there is no magnetic field to truncate the disk above the stellar surface, so all thick lines (solid and dashed, black and red) overlap.

of Matt & Pudritz (2008a). This formulation is based upon analytic calculations going back to Weber & Davis (1967), in which the torque from a one-dimensional wind is given by

$$T_w = -\dot{M}_w \Omega_* r_A^2, \quad (8)$$

where r_A is the Alfvén radius, the location where the wind speed equals that of magnetic Alfvén waves. In real stellar winds, the flow is aspherical, due to (e.g.) rotation and magnetic geometry. Matt & Pudritz (2008a) computed solutions for two-dimensional (axisymmetric) solar-like stellar winds, using numerical magnetohydrodynamic simulations. They used the simulations to compute T_w and \dot{M}_w and then used equation (8) to define r_A , which in this context represents the mass-loss-weighted average of the Alfvén radius in the multi-dimensional flow. For variations in the magnetic field strength, stellar radius, surface gravity, and mass loss rate, the solutions for r_A are well-fit by the following

$$\frac{r_A}{R_*} = K \left(\frac{B_*^2 R_*^2}{\dot{M}_w v_{esc}} \right)^m, \quad (9)$$

where K and m are fit constants. For the cases with a dipole magnetic field, the simulations of Matt & Pudritz

(2008a) indicate $K \approx 2.11$ and $m \approx 0.223$, which we adopt in this work. A similar numerical study of the torque from the winds of massive stars (Ud-Doula et al. 2008, 2009) found a relationship similar to equation (9), with $m = 1/4$ and K of the order of unity. By contrast, studies of cold, magnetocentrally-driven flows (e.g., Pelletier & Pudritz 1992; Spruit 1996; Anderson et al. 2005) imply $m = 1/3$.

2.4.3. Total Torque and Equilibrium Spin Rate

The total torque on the star, used in equation (5), is the sum of the star-disk interaction torques and the stellar wind torque,

$$T_* = T_a + T_m + T_w. \quad (10)$$

The spin rate of any star-disk interacting system generally evolves in such a way as to tend toward a theoretical “equilibrium spin rate,” at which the net torque on the star is zero:

$$T_* = 0 \quad (\text{in spin equilibrium}). \quad (11)$$

For the values of the magnetic field opening and coupling parameters considered in this paper ($\gamma_c = 1$ and $\beta = 0.01$), Matt & Pudritz (2008b) showed that the magnetic torque T_m is generally negligible compared to the

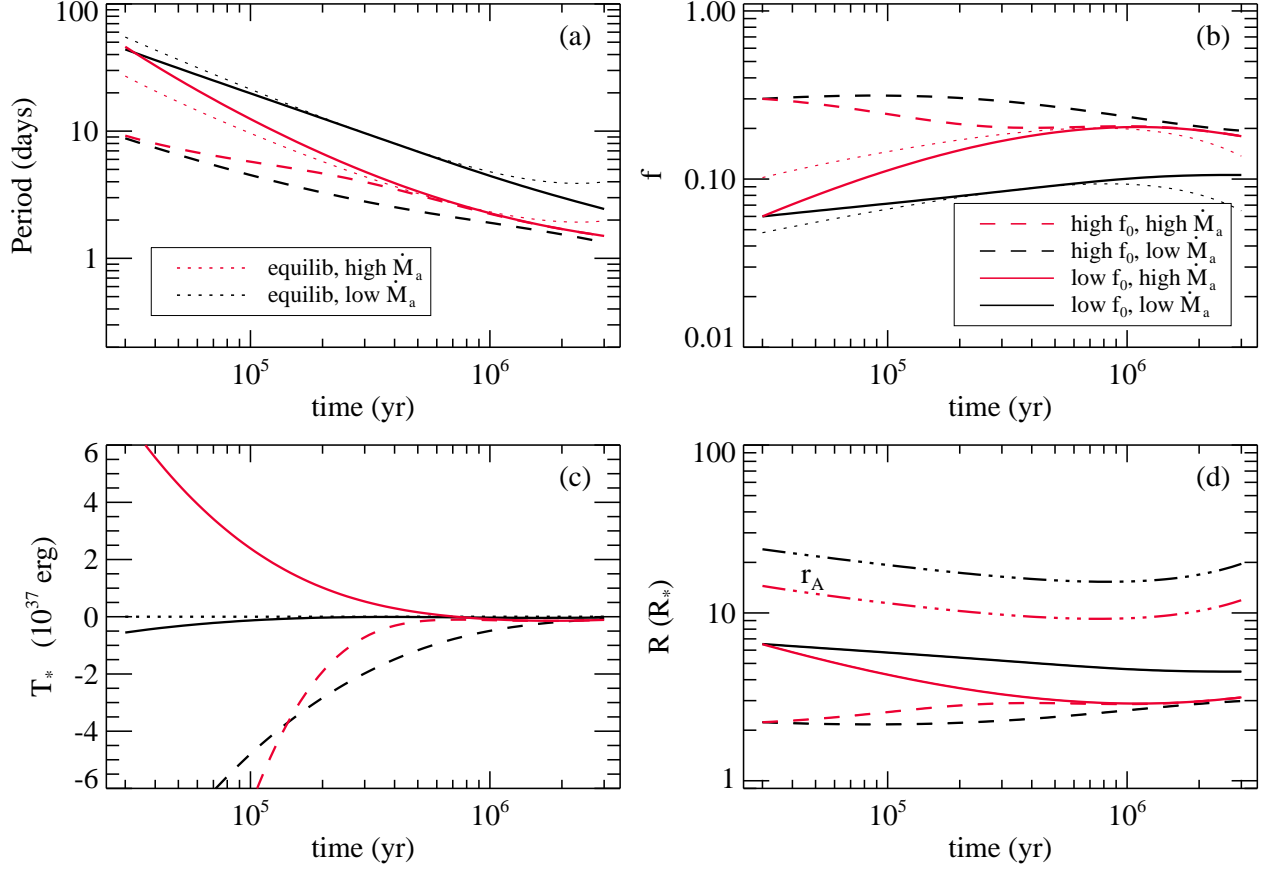


Figure 2. Results for $B_* = 500$ G and $\dot{M}_w/\dot{M}_a = 0.1$, in the same format as Figure 1. In panels (a) and (b), the dotted red and black lines show the theoretical equilibrium rotation rates (eq. [12]) for the high and low accretion rates, respectively. In panel (d), the dash-triple-dotted red and black lines show the stellar wind Alfvén radius (§2.4.2) for the high and low accretion rates, respectively. Also in panel (d), the thin and thick solid lines of a given color and type are indistinguishable, since R_t is very close to R_{co} in all four cases.

stellar wind torque T_w . Thus, the spin equilibrium is approximately characterized by $T_a = -T_w$. This predicts an equilibrium spin rate, expressed as a fraction of breakup speed, given by (eq. [18] of Matt & Pudritz 2008b),

$$f_{\text{eq,sw}} = K^{-3/2} \chi^{(6m-3)/4} \Psi^{-3m/2}, \quad (12)$$

where

$$\Psi \equiv \frac{B_*^2 R_*^2}{\dot{M}_a v_{\text{esc}}}. \quad (13)$$

Equation (12) assumes that the truncation radius is always near the corotation radius, which turns out to be true in the models with non-zero magnetic field presented in this paper. Below, we will use the predicted equilibrium spin rate of equation (12) to compare with the results of our spin evolution models.

2.5. Numerical Method

The coupled equations (3), (4), and (5) describe the evolution of the system in time. We wrote a computational code that solves these simultaneously, using the fourth-order Runge-Kutta scheme of Press et al. (1994), starting from $t_0 = 3 \times 10^4$ yr and ending at 3 Myr. The code is described in more detail in Paper I.

3. RESULTS

Table 1
Model Parameters

Case	χ	B_* (Gauss)	$\dot{M}_{a0} (M_\odot/\text{yr})$	f_0	Figure
$B_* = 0$	0	0	$10^{-8}, 10^{-7}$	0.06, 0.3	1
W1	0.1	500	$10^{-8}, 10^{-7}$	0.06, 0.3	2
W2	0.1	2000	$10^{-8}, 10^{-7}$	0.06, 0.3	3
W3	0.01	2000	$10^{-8}, 10^{-7}$	0.06, 0.3	4

Table 1 contains the parameters for each case presented in this section, listed in order of their presentation and grouped by the figures in which the results appear. For each case, we present the evolution of the system for the 4 possible combinations of 2 different initial mass accretion rates (parameterized by \dot{M}_{a0}) and 2 different initial spin rates (f_0). The “ $B_* = 0$ ” case is identical to that of Paper I, and we include it here to facilitate comparison with the new results (cases W1–W3).

It is instructive first to examine the non-magnetic case, $B_* = 0$, in which there are no magnetic fields. Figure 1 illustrates the evolution of the spin rate—expressed as the spin period (panel (a)) and as a fraction of breakup speed (panel (b))—the total torque experienced by the star (panel (c)), and the radial locations of the disk inner edge (R_t) and corotation radius (R_{co}) (panel (d)). In the $B_* = 0$ case, the disk extends all the way to the surface of the star ($R_t = R_*$, as indicated by the thick lines in

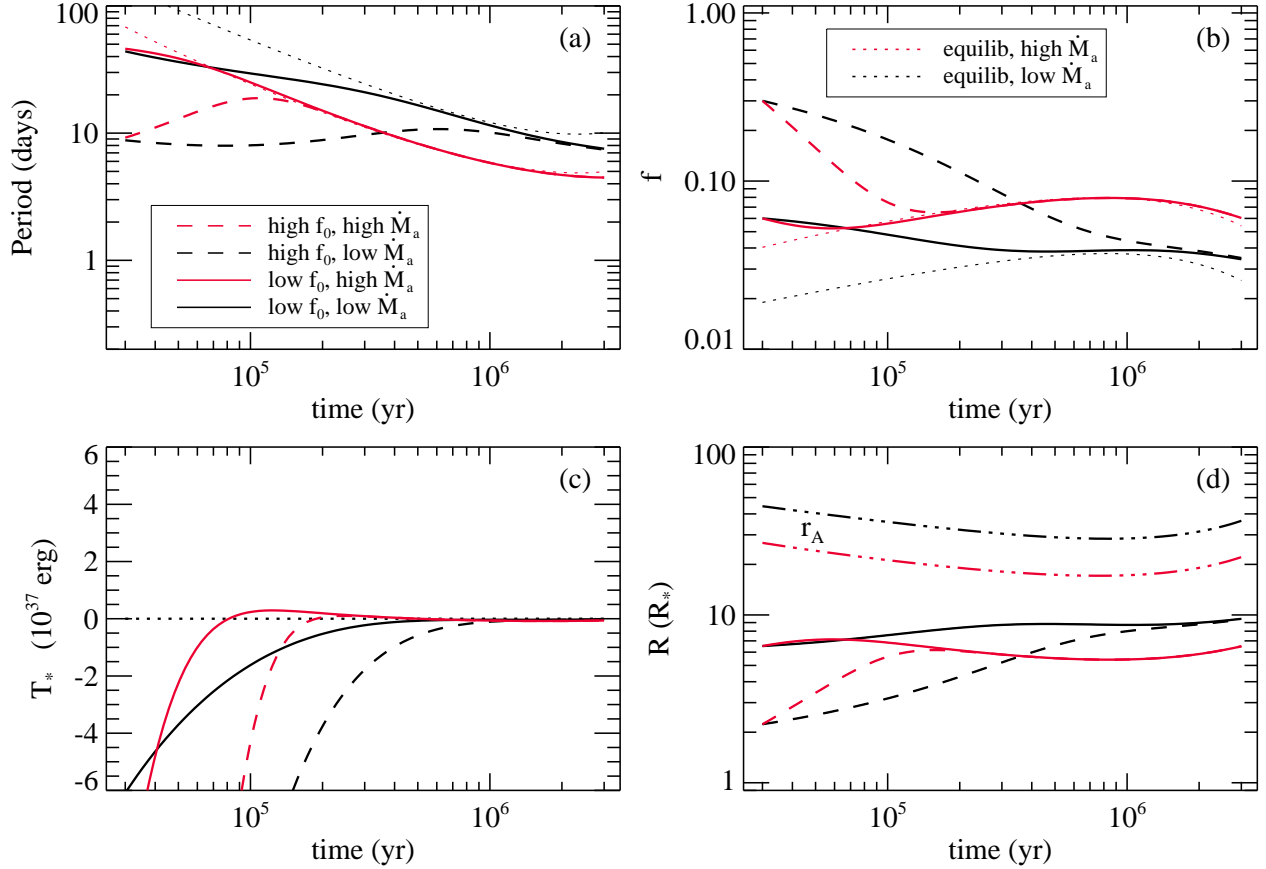


Figure 3. Results for $B_* = 2000$ G and $\dot{M}_w/\dot{M}_a = 0.1$, in the same format as Figure 2. In panel (d), the thin and thick lines of a given color and type are indistinguishable, since R_t is very close to R_{co} in all four cases.

panel d), and the torque experienced by the star (panel c) is solely the accretion torque, $T_a = \dot{M}_a \sqrt{GM_* R_t}$ (since $T_m = T_w = 0$).

In all 4 models shown in Figure 1, the stellar spin rate increases monotonically in time, due to the accretion of disk material with high specific angular momentum and due to the contraction of the star. Only the most extreme model (with the slowest initial spin and lowest accretion rate, black solid line in panels (a) and (b)) has a spin period in the range 1–3 days during the age range of 1–3 Myr. The other 3 models have spin periods substantially less than a day, in the same age range.

All subsequent cases (W1–W3) have a non-zero magnetic field and use $\gamma_c = 1$ and $\beta = 0.01$ for the star-disk magnetic connection parameters, which are appropriate values to include the effects of strong magnetic coupling to the disk and the opening of magnetic field lines by azimuthal twisting (see Matt & Pudritz 2005b, and Paper I). Thus, in addition to the accretion torque, the model stars experience spin-up and spin-down torques (T_m) associated with a magnetic connection over a finite region of the disk. Also, cases W1–W3 include the mass loss (χ) and torque (T_w) due to stellar winds (as described in §2).

Figure 2 shows the results for the four models in the W1 case, in which the star has a 500 Gauss magnetic field and stellar wind mass loss rate that is 10% of the disk accretion rate ($\chi = 0.1$). In this Figure, the line colors and styles have the same meaning as Figure 1,

with a few additions. Panels (a) and (b) include dotted lines that indicate the equilibrium spin value predicted by equation (12) for the high and low mass accretion rate models (red and black lines, respectively). In panel (d), the dash-triple-dotted lines indicate the location of the Alfvén radius in the stellar wind (eq. [9]) for the models with high and low accretion rate (and thus high and low wind outflow rate; red and black lines, respectively).

By comparing Figures 1 and 2, it is clear that the stellar spin evolution is substantially influenced by the presence of a 500 G field and accretion-powered stellar wind with $\chi = 0.1$. In the age range of 1–3 Myr, all four models in Figure 2 have spin periods in the range of 1–5 days, which corresponds to spin rates between 10% and 20% of breakup. As visible in panel (d), the truncation radius is very close to the corotation radius (such that the thick and thin lines overlap in the plot), for all models at all times. The Alfvén radius in the stellar wind (panel (d)) for all models remains in the range of approximately 10–30 R_* .

Panels (a) and (b) show the equilibrium spin rate (dotted lines) predicted by equation (12) under the assumption that the spin evolution is dominated by a balance between the accretion (spin-up) torque and stellar wind (spin-down) torque. In Figure 2, the two models corresponding to a high accretion rate (red solid and dashed lines) approach the equilibrium spin rate at an age of a few times 10^5 yr. After this time, the initial condition for the spin rate of these models has effectively been

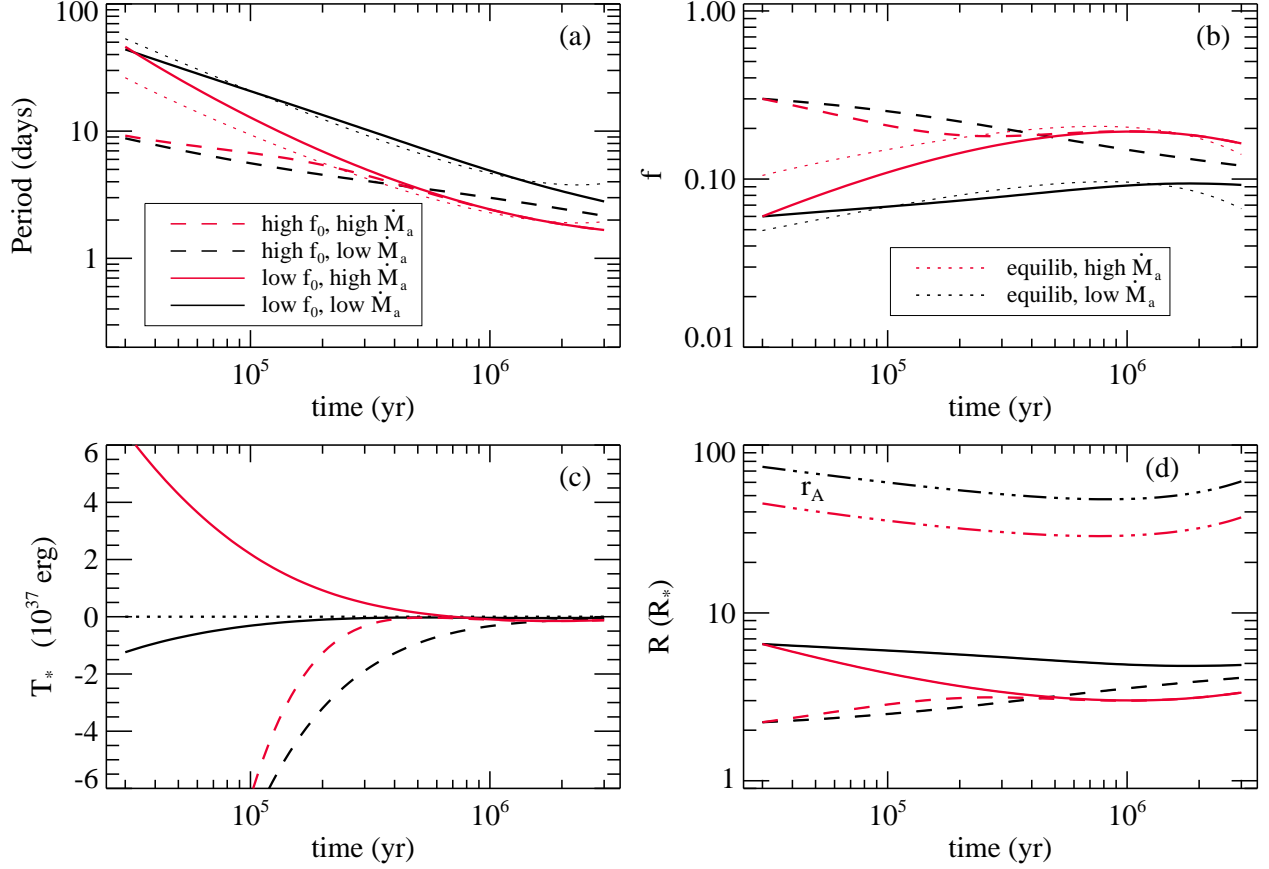


Figure 4. Results for $B_* = 2000$ G and $\dot{M}_w/\dot{M}_a = 0.01$, in the same format as Figure 2. In panel (d), the thin and thick lines of a given color and type are indistinguishable, since R_t is very close to R_{co} in all four cases.

“erased,” in a sense that the subsequent spin rate is insensitive to the initial rate. For the models with low accretion rate (black solid and dashed lines), the torque is not strong enough to drive the spin rate to the equilibrium value within 3 Myr. The case with a slow initial spin rate (black solid line) evolves near the equilibrium value, but this is only due to a coincidence between the initial and equilibrium spin rates.

Figure 3 shows results for the W2 case, which is the same as W1, except that the magnetic field is 4 times stronger ($B_* = 2000$ G). By comparing Figures 2 and 3, it is clear that the stronger magnetic field results in slower spin rates. In the age range of 1–3 Myr, all four models in Figure 3 have spin periods in the range of 4–12 days, corresponding to spin rates between 3% and 8% of breakup. The models with high accretion rate in the W2 case (Fig. 3, red solid and dashed lines) approach the equilibrium spin rate after $\sim 10^5$ yr, sooner than the weaker field case (W1). Furthermore, the models with low accretion rate (black solid and dashed lines) approach the equilibrium spin rate after $\sim 10^6$ yr. In all models and at all times, the truncation radius is very close to the corotation radius (such that the thick and thin lines overlap in panel (d)), and the Alfvén radius in the winds remains in the range of 15–50 R_* .

Figure 4 shows results for the W3 case, which is the same as W2, except that the stellar wind outflow rate is 10 times less ($\chi = 0.01$). A lower wind mass outflow rate, if all else is equal, means a lower spin-down torque

from the stellar wind. Thus, the accretion-powered stellar wind in the W3 case is less effective at spinning down the star than the W2 case. A comparison between Figures 4 and 2 reveals that the W3 case is qualitatively and quantitatively very similar to the W1 case, which has a higher wind outflow rate but a weaker magnetic field. The similarity in the spin evolution of these two cases is a consequence of the dependence of the stellar wind torque on the parameters changed. Specifically, equations (8) and (9) and $m = 0.223$ results in $T_w \propto \dot{M}_w^{0.55} B_*^{0.89}$, which means that the factor of 10 difference in \dot{M}_w is almost completely compensated by the factor of 4 difference in B_* . While the stellar wind torques are similar in these two cases, the Alfvén radius in the wind has a different dependence on these parameters, and thus the models in the W3 case have a much larger Alfvén radii than the W1 case (compare the dash-triple-dotted lines in panel (d)).

It is instructive to compare the cases presented here with the cases in Paper I. Case W1 is identical to case O1 in Paper I, except that W1 includes the effect of an accretion-powered stellar wind, via a nonzero value of the mass-loss parameter χ . Likewise, cases W2 and W3 are similar to O2 of Paper I. A comparison between W1–W3 (Figs. 2–4) and O1/O2 (Figs. 6 and 7 of Paper I) indicates that the cases with stellar winds spin substantially slower than the cases without. For the range of magnetic field strengths, accretion rates, initial spin rates, and mass outflow rates considered in cases W1–W3, the mod-

els exhibit rotation periods within the range of approximately 1–10 days in the age range of 1–3 Myr. These rotation periods correspond to spin rates in the range of approximately 5%–20% of breakup speed and lie within the bulk of the distribution observed in stars of similar age and mass (see §1).

For all of the models in cases W1–W3 that approach an equilibrium, the spin rates closely follow the prediction of equation (12). Since that equation assumes a balance solely between the accretion torque and a stellar wind torque ($T_* = -T_w$), the fact that some models follow this prediction indicates that the magnetic torque from the star-disk connection (T_m) is negligible in those models. More generally, Matt & Pudritz (2008b) showed that, for the strong coupling case considered here (i.e., $\beta = 0.01$ and $\gamma_c = 1$), the stellar wind torque dominates over the spin-down portion of the magnetic torque T_m as long as the Alfvén radius in the stellar wind (r_A) is $\lesssim 84R_*$. This is true during the entire evolution for all models presented here (see dash-triple-dotted lines in panel (d) of Figs. 2–4). Thus, it is the stellar wind torque, not the star-disk magnetic connection, that is responsible for the slower spin of these models relative to the non-magnetic case.

4. COMPARISON BETWEEN APSW AND DISK LOCKING MODELS

For the magnetic torque model and chosen parameters presented in sections 2 and 3, we showed that the spin-down torque from APSWs completely dominates over any spin-down torques that may arise from the magnetic connection between the star and disk. Thus, the evolution of the stellar spin is primarily determined by a competition between the spin-down torques from an APSW and a spin-up via the accretion torque (hereafter, the “APSW model”). However, given the large number of unknowns regarding real systems, it is instructive to compare the predictions of different star-disk interaction models for a range of possible conditions and assumptions.

As discussed earlier, in these systems the spin rate of the star always tends toward the equilibrium spin rate at which the net torque on the star would be zero. If the spin-up or spin-down time is short (i.e., for a strong net torque) compared to the evolution timescale, the star’s spin will remain close to this equilibrium value. Whether or not the torque is strong enough to keep the star spinning near equilibrium depends upon many factors (e.g., the accretion rate \dot{M}_a and magnetic field strength B_*), which also may be varying in time. Thus it is not generally expected that all systems should be in equilibrium. However, for the purpose of comparing different models, it is convenient and particularly instructive to compare the predictions of the equilibrium spin rate for each model. When a particular model predicts a slower spin rate compared to other models, it simply means that the spin-down torques are generally stronger in that model.

The equilibrium spin rate predicted by the APSW model, expressed as a fraction of breakup speed, is given in equation (12). In Figure 5, the solid lines show this

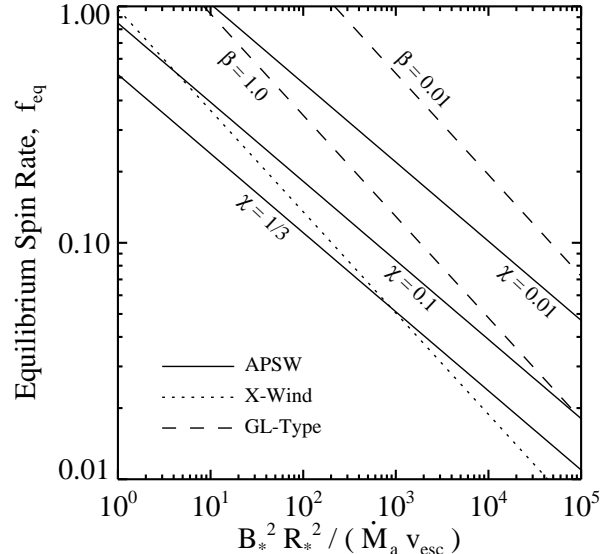


Figure 5. Predicted equilibrium spin rates of different star-disk interaction models as a function of the dimensionless parameter Ψ (eq. [13]). The solid lines show the prediction of the APSW model (determined by eq. [12], with $K = 2.11$ and $m = 0.223$) for three different values of χ , as indicated. The dashed lines show the predictions for the Ghosh & Lamb-type disk locking model of Matt & Pudritz (2005b) (determined by eq. [14], with $C = C(\beta, \gamma_c)$ for $\gamma_c = 1$ and two different values of the magnetic coupling parameter β , as indicated). The dotted line shows the prediction of the X-wind model (determined by eq. [14] with $C = 0.974$).

predicted equilibrium spin rate as a function of the dimensionless parameter Ψ and for 3 different values of $\dot{M}_w/\dot{M}_a \equiv \chi = 1/3, 0.1$, and 0.01 . As discussed in section 2, we adopt values of $K = 2.11$ and $m = 0.223$, which results in a power-law slope of $-3m/2 \approx -0.33$ in the Figure. The plot covers a range in Ψ from 1 to 10^5 , which is chosen to approximately reflect the possible range in real systems, obtained by choosing extreme values of parameters from the range that is observed for T Tauri stars (e.g., Hartmann et al. 1998; Gullbring et al. 1998; Johns-Krull & Gafford 2002; Robberto et al. 2004; Sicilia-Aguilar et al. 2006; Bouvier et al. 2007).

Of the various star-disk interaction studies in the literature, there are two other types of general models that predict an equilibrium spin rate, and with which we will compare the predictions of the APSW model. These are the Ghosh & Lamb type (GL-type) models (e.g., Paper I; Camenzind 1990; Koenigl 1991; Cameron & Campbell 1993; Cameron et al. 1995; Yi 1994, 1995; Lovelace et al. 1995; Armitage & Clarke 1996; Matt & Pudritz 2005b; Zweibel et al. 2006), which are based on the original accreting magnetized star model of Ghosh & Lamb (1978), and the X-wind model (Shu et al. 1994a,b; Najita & Shu 1994; Ostriker & Shu 1995; Shu et al. 1995; Mohanty & Shu 2008). Both the GL-type and X-wind models assume that the magnetic connection between the star and disk alone is responsible for removing the necessary angular momentum, and both neglect the influence of stellar winds. In their equilibrium state, these are often referred to as “disk locking” models (Choi & Herbst 1996). The predicted equilibrium spin

rate for both types of models can be expressed as

$$f_{\text{eq,dl}} = C\Psi^{-3/7}, \quad (14)$$

where C is a dimensionless constant that takes into account various assumptions in the models, and Ψ is the same as defined in equation (13).

The various disk-locking models in the literature differ in their assumptions, which is reflected in a different value of C . The star-disk torque model of Matt & Pudritz (2005b) (used in the present paper) is a GL-type model that includes the effect of magnetic field opening (via the parameter γ_c) and magnetic coupling strength (via the parameter β). That work showed that the constant² C is a function of only γ_c and β , and different choices of these can result in C values that span the range of GL-type models presented in the literature. Uzdensky et al. (2002) demonstrated that a value $\gamma_c = 1$ (adopted in the present work) is the most appropriate to properly take into account the effect of the opening of magnetic field lines due to differential twisting between the star and disk.

The dashed lines in Figure 5 show the prediction of GL-type models for $\gamma_c = 1$ and two different values of β (0.01 and 1.0, corresponding to $C \approx 10.1$ and $C \approx 2.49$, respectively). The upper-most line corresponds to the GL-type model used to compute the magnetic star-disk torques in the spin-calculations of the present paper (i.e., for $\beta = 0.01$). It is clear that this GL-type model predicts an equilibrium spin rate that is faster than the APSW model, for the entire plotted range of Ψ , and as long as χ is greater than a few thousandths. This is just another way of demonstrating that, when the mass loss is high enough, APSWs are much more effective at spinning down stars than a GL-type star-disk interaction alone.

The effective value of β in real systems is not well constrained. In the GL-type models with $\gamma_c = 1$, Matt & Pudritz (2005b) showed that the value of $\beta = 1$ results in the minimum value for C and thus represents the case where the GL-type model torques would be the most effective at spinning the star down. The bottom-most dashed line in Figure 5 shows the prediction for this special case. It is clear that the APSW model generally predicts a slower spin rate for $\chi \sim 0.1$ than the GL-type models with any value³ of β . For $\chi \sim 0.01$, the APSW model predictions are of a similar magnitude as those of a GL-type model with $\beta = 0.1$. While the effective value of β in real systems is uncertain, it seems likely that the inner disks of young stars exist in a state of high magnetic Reynolds number ($\beta \ll 1$), and thus that the GL-type spin-down torques are relatively weak.

In the X-wind model, the angular momentum is assumed not to accrete onto the star, but rather is intercepted at the inner edge of the disk (the “X-point”) and then carried out of the system by a wind (the “X-wind”) from the X-point. The fiducial model of Shu et al.

(1994a) and Ostriker & Shu (1995) supposes that the wind outflow rate from the X-point is $\sim 1/3$ times the accretion rate, which results in a predicted equilibrium spin rate that is given by equation (14), with a value of $C \approx 0.974$. The dotted line in Figure 5 shows this predicted spin rate of the X-wind model. It is clear that this model also predicts slower spin rates than the GL-type models.

Both the APSW and X-wind models employ a wind to remove angular momentum from the system. Thus, it is perhaps not surprising that the predicted spin rate of the APSW model with the same mass outflow rate as the X-wind, $\chi = 1/3$ (bottom solid line in Fig. 5), is quantitatively similar to the predictions of the X-wind. Furthermore, it can be shown that the factor C in the X-wind model depends upon the mass loss rate to the power of $-3/7$, which is very close to the dependence of the APSW model prediction on the mass loss rate (in eq. [12], $f \propto \chi^{-0.42}$, for the adopted value of $m \approx 0.223$).

Although the predicted equilibrium spin rates are quantitatively similar, the physical picture of APSW and X-wind models have some important differences. In the X-wind, the wind is magnetically connected to, and removes angular momentum from, the X-point (not from the star, as in a stellar wind). The X-wind model is developed under the assumption that there is no net torque on the star and that the X-point is located at the corotation radius. Thus, the balancing of angular momentum is evaluated at the X-point (rather than on the star), and this leads to a requirement for a certain amount of stellar magnetic flux to be pinched, or “trapped,” within the X-point. Having the flux is trapped at the X-point avoids the large-scale opening of magnetic field (which is a problem for the GL-type models) and also produces a geometry in which magneto-centrifugal forces may provide a natural explanation for the acceleration of the wind. However, the biggest problem for the X-wind model is that the amount of flux trapping required at the X-point raises questions of dynamical stability (e.g., Uzdensky 2004), and such a magnetic field configuration has not yet been demonstrated to exist in a dynamical model. Furthermore, since the model assumes no net torque on the star (i.e., it assumes the star to be in spin equilibrium), the model provides little information about how angular momentum may flow from accreting material outward to the X-point, and across the X-point, in order to be removed in the X-wind and/or via transport processes in the disk (Ferreira et al. 2000). The assumption of equilibrium also means that the model cannot address how these systems evolve (e.g., one cannot make plots such as panels [c] in Figs. 1–4), nor whether or how a system will reach or approximate the equilibrium state and magnetic field configuration described.

By contrast, the APSW model calculates the spin-up and spin-down torques acting on the star from various processes (i.e., at different geographical locations on the star). The theoretical equilibrium state corresponds to when the net torque is zero, but the model can be used to compute the net torque in any state. The magnetic field configuration is that of the stellar magnetic field, which has a significant amount of flux that is opened by various dynamical processes (e.g., see discussion in Matt & Pudritz 2005b). Numerical, dynamical

² For convenience here, we have absorbed all constant factors into the value of C in equation (14), as compared to equation (25) of Matt & Pudritz (2005b).

³ This statement is true for $\gamma_c = 1$. Most of the GL-type models in the literature have not taken into account the opening of the magnetic field, which is equivalent to assuming $\gamma_c = \infty$. In this case, and especially when β is taken to be small (e.g., as in the model of Cameron & Campbell 1993), the spin-down torque is (artificially) enhanced and can be arbitrarily large.

simulations (e.g., Hayashi et al. 1996; Goodson et al. 1997; Miller & Stone 1997; Goodson et al. 1999; Fendt & Elstner 1999, 2000; Matt et al. 2002; Küker et al. 2003; Rekowski & Brandenburg 2004, 2006; Long et al. 2005; Romanova et al. 2005; Bessolaz et al. 2008; Zanni & Ferreira 2009; Fendt 2009; Romanova et al. 2009; Long et al. 2011; Romanova et al. 2011) generally show that such a magnetic field configuration is a natural and general consequence of the star-disk interaction. It is the open stellar field lines that are primarily responsible for the spin-down torque on the star, via a wind flowing along the field. The amount of magnetic flux participating in the wind is not a free parameter, but is determined in a dynamically self-consistent way via the MHD simulations used to compute equation (8) for the stellar wind torque (Matt & Pudritz 2008a). Thus, there is no conceptual nor dynamical problem with the magnetic field configuration of the APSW model. However, the biggest open question for APSW model is whether and/or how the accretion power in the system can drive a wind that is magnetically connected to the star and that has a mass outflow rate high enough to extract significant angular momentum. This is discussed further in section 5.

It is clear from Figure 5 that the APSW predicts a slope that is somewhat shallower than the disk-locking models. This fact could in principle be used to discriminate between the models (e.g., similar to Johns-Krull & Gafford 2002), although this may not be possible with existing data. The difficulty is due to at least 3 factors: a) there are large observational uncertainties for the quantities plotted in Figure 5 and few stars for which these quantities have been measured; b) not all systems are expected to be in spin-equilibrium; and c) these systems are typically highly time-variable (e.g., Hartmann 1997), which means that a realistic spin-equilibrium (net zero torque) state may only exist in a time-averaged sense—or in a statistical sense, for a large collection of stars. Furthermore, the predicted slope for the APSW model may be different, depending upon a few unknowns. The form of equation (12) assumes that the disk truncation radius is close to the corotation radius (Matt & Pudritz 2008b), which will not necessarily be true in all systems. Also, the value of the power law parameter m depends upon the conditions in the stellar wind, and a number of factors (discussed in §5) may affect this value.

Finally, we note that in the interest of performing direct and quantitative comparisons, this section has focused on the three classes of star-disk interaction models for which a simple prediction for a hypothetical equilibrium spin rate is possible. Thus, there are a number of other ideas in the literature that we have neglected and that nonetheless deserve further attention. For example, time-variability of the accretion rate onto the star may strongly influence stellar spin evolution (e.g., Popham 1996; D’Angelo & Spruit 2010), and the dynamics of the interface region that exists between the open magnetic flux threading the star and disk may also be important for extracting angular momentum (e.g., Hirose et al. 1997; Ferreira et al. 2000; Romanova et al. 2009, Zanni & Ferreira, in preparation).

5. SUMMARY AND DISCUSSION

Paper I presented a model for computing the evolution of mass, radius, and spin rate of an accreting, one solar mass star during the Hayashi phase (from 3×10^4 yr to 3 Myr). The spin of the star evolves from its initial value due to changes in the moment of inertia (due to stellar contraction) and to external torques. To compute the external torques, Paper I included only the magnetic star-disk interaction torque formulation of MP05, and neglected any torque along open field lines. That work showed that, for strong magnetic coupling to the disk ($\gamma_c = 1$ and $\beta = 0.01$), cases with either $B_* = 500$ G or 2000G result in spin evolution that is only slightly changed from the non-magnetic case. In other words, when the magnetic coupling is strong and $B_* \lesssim 2000$ G, the spin-down torque arising in the star-disk interaction is negligible for the spin rates and mass accretion rates considered.

The goal of the present paper was to determine under what conditions the additional spin-down torque from stellar winds may significantly affect the spin evolution and produce a range of spin rates consistent with the observed range. Thus, we have extended the model of Paper I (as described in §2) to include an additional spin-down torque due to the stellar wind. As stellar wind torques depend upon most of the same parameters as star-disk interaction torques, including a stellar wind has introduced only one new parameter, the mass outflow rate of the wind. Here, we consider the case where the mass outflow rate is some fixed fraction (χ) of the accretion rate, as may be expected for a wind that is somehow driven by accretion power (Matt & Pudritz 2005a).

In section 3, we found that the cases with $B = 2000$ G and mass loss rates of $\chi = 0.1$ resulted in spin rates in the range of ~ 5 –10 days, in the age range of 1–3 Myr. For the two cases with either a lower mass loss rate ($\chi = 0.01$) or magnetic field strength ($B = 500$ G), the resulting spin rates were in the range of 1–5 days (for 1–3 Myr ages). These two cases exhibited similar spin evolution because the stellar wind torques were nearly identical in both cases (i.e., there is a degeneracy between B_* and \dot{M}_w in the stellar wind torque, eq. [8] and [9]; discussed in §3). Overall, the magnetic cases presented in section 3 resulted in stellar spin periods in the range of approximately 1–10 days, in the age range of 1–3 Myr. This range covers the range of the most populated regions of the observed spin period distributions of clusters with similar ages (e.g., Stassun et al. 1999; Herbst et al. 2002; Rebull et al. 2004; Lamm et al. 2005; Herbst et al. 2007; Irwin & Bouvier 2009). In general, accretion-powered stellar winds may explain the slowest rotators as those stars with the strongest magnetic fields, lowest accretion rates, and/or highest stellar wind mass outflow rates (relative to the accretion rate).

We found that some cases that had torques strong enough to drive the system close to an equilibrium spin rate (e.g., as in Fig. 3). Spin equilibrium states are interesting because the initial conditions are “erased,” and the spin rate depends only on present conditions (e.g., accretion rate, magnetic field strength, etc.). However, for the conditions considered here (in particular, for strong magnetic coupling), the magnetic spin-down torques arising in the star-disk interaction were completely negli-

ble. Thus, these stars’ equilibrium rotation rates are not physically linked to the rotation rate of the disk inner edge (as in disk locking) but rather are described by a simple balance between a spin-up torque from accretion and a spin-down torque from a stellar wind. This simple balance allows for an analytic formula for predicting the equilibrium (net-zero torque) spin rate (e.g., eq. [12]).

While we have necessarily made a number of simplifying assumptions, we have whenever possible adopted the same assumptions that are typically used in previous models in the literature (in particular, the disk-locking models). Our approach in Paper I and here has been deliberately systematic, so that each additional component or assumption in the model can be understood in turn. In this way, our approach best serves to highlight the influence of the opening of the magnetic field due to star-disk differential rotation (Paper I) and the influence of an accretion-powered stellar wind (present paper), *relative* to the previous studies that do not include these effects. We have explored a range of conditions that are consistent with observations of T Tauri stars, but we have not explored all of parameter space, and there remain uncertainties inherent to various adopted assumptions and approximations. Thus, while our quantitative results should be viewed as approximate, the results relative to other studies/models in the literature are robust.

With this in mind, we compared the predicted equilibrium spin rate of the APSW scenario to the predictions of two types of disk-locking models, the Ghosh & Lamb type and X-wind models (§4). Overall, this comparison and our results in general demonstrate that APSWs can explain the observed distribution of young star spins in a similar way as the classical disk locking picture, while at the same time avoiding the problem of magnetic field line opening (for the GL-type models), as well as the assumption of spin equilibrium and requirement of significant flux trapping (for the X-wind model).

The APSW scenario has one additional parameter, the mass loss rate in the wind. For the assumptions adopted here, we found that in order for the APSWs to have a significant influence, the mass loss rates should be at least of the order of a percent of the accretion rate. It still remains to be shown whether and/or how the energy derived from the accretion process may drive a wind that is magnetically connected to the star, and with sufficiently high mass outflow rate. Such winds would not likely be driven significantly by thermal pressure (due to a rapid cooling time Matt & Pudritz 2007), nor by magneto-centrifugal effects (from slowly-rotating stars), but Alfvén waves may be important (e.g., Decampli 1981; Hartmann et al. 1982; Suzuki 2007). Cranmer (2008, 2009) demonstrated that Alfvén waves generated by the accretion process in T Tauri stars are capable of driving enhanced stellar winds. The mass loss rates derived by those models were typically $\chi \lesssim 0.01$. There is a hard energetic upper limit of $\chi \lesssim 0.6$ for APSWs (Matt & Pudritz 2008b), and values close to this will have observational consequences that may already be ruled out in some systems (Zanni & Ferreira 2011). Thus, values of χ much greater than 10–20% seem unlikely, in general. Clearly, more work is needed to determine what is the mass loss rate along the stellar magnetic field and how this should depend upon system parameters.

ters.

Measurements of the magnetic field strengths of young stars suggest that the stellar surface is blanketed with complex magnetic fields with a strengths of ~ 2 kG (e.g., Safer 1998; Bouvier et al. 2007; Johns-Krull 2007; Yang & Johns-Krull 2011). However, even when complex magnetic fields are present, it is the large-scale (dipole) component that is the most important for the star-disk interaction and torques on the star (e.g., Gregory et al. 2008). The dipole components have been measured via spectropolarimetry for at least 10 accreting T Tauri stars to date (Donati et al. 2007, 2008; Hussain et al. 2009; Donati et al. 2010a,b, 2011b,a; Donati, J. F. et al. 2011; Skelly, M. et al. 2011), and the equatorial field strengths of the dipole components range from $\sim 100 - 1000$ G, with the top of this range determined by just two of the stars ($B_* \approx 600$ G for BP Tau, and $B_* \approx 1000 - 1500$ G for AA Tau; Donati et al. 2008, 2010a). The disk-locking models usually require field strengths of ~ 1000 G to explain the slowest rotators, and the weakest equatorial field strength we have considered in the present work is $B_* = 500$ G. The APSW scenario can, in principle, make up for a weaker magnetic field by having a larger mass outflow rate, although the largest values of χ considered in the present paper are already approaching the upper limits (see, e.g., Matt & Pudritz 2008b; Zanni & Ferreira 2011). To better constrain the models, it will be important to have magnetic field measurements, particularly of the large-scale components, for a larger sample of pre-main-sequence stars.

In addition to those discussed above, there remain a number of caveats to the present work. While we have adopted a relatively sophisticated model for the torques on the star, we use a simplified treatment for the accretion history, the evolution of the magnetic field, and the structure and evolution of the star itself. In order to be able to make a more meaningful comparison with observations, and especially to be able to evolve the system to much later times, it will be necessary to improve the theoretical treatment of these components.

For example, the present treatment of the accretion does not allow for a possible state of the system in which the disk is truncated outside of the corotation radius, the so called “propeller” regime. In this regime, there is generally no accretion onto the star (e.g., Illarionov & Sunyaev 1975; Sunyaev & Shakura 1977), or the accretion is intermittent (e.g., Romanova et al. 2005; D’Angelo & Spruit 2010). In the present work, we are considering systems with strong magnetic coupling (large magnetic Prandtl number in the disk) and relatively slow rotation. Under these conditions, the magnetic spin-down torque on the star—which acts to spin up the disk and can potentially truncate the disk outside of R_{co} —is relatively weak compared to other torques in the system. Thus, we don’t expect the propeller regime to be important for most of the evolution these systems. However, there may be times in the history of such stars (e.g., toward the end of the accretion phase) in which the propeller regime is important for the angular momentum loss. Properly capturing the transition between accreting and propeller states requires a self-consistent treatment of the evolution of the accretion disk (as in, e.g., Armitage & Clarke 1996; D’Angelo & Spruit 2010). In the present model, we imposed the accretion rate onto

the star, which implicitly assumes that the disk is always able to transport excess angular momentum given to it by the star (see, e.g., Matt & Pudritz 2005b). To explore the influence of the propeller regime on the long-term spin evolution, future models should include both self-consistent disk evolution and sophisticated treatment of the torques on the star.

Finally, all of our conclusions regarding the effectiveness of stellar wind torques relies on the particular formulation for the torque from Matt & Pudritz (2008a). While this is the most appropriate formulation for low-mass-star winds that exists in the literature, there remain a few open questions about its use in the present work. First of all, that formulation was derived for an isolated star, and we have simply added this torque to our model, which also assumes the presence of an accretion disk and associated interaction torques in a non-self-consistent way. It is not yet clear how the presence of a disk will influence the stellar wind, and in particular how it may influence the dependence of the stellar wind torque on parameters (e.g., the value of m). Also, the formulation of Matt & Pudritz (2008a) was based upon simulations of a star with a singular spin rate ($f = 0.1$) and a solar-like wind acceleration mechanism. It is encouraging that a study of angular momentum flow from massive stars (Ud-Doula et al. 2008, 2009), which includes a very different wind acceleration mechanism and a range of spin rates, found a similar power law relationship for the torque, but more studies are warranted. Lastly, all stellar wind torque formulations in the literature are based upon simple (e.g., dipolar) magnetic geometries, while we know that T Tauri stars possess complex magnetic field structures. In future work, it will be important to determine whether the presence of an accretion disk, more complex magnetic geometries, or different wind acceleration mechanisms will significantly enhance or suppress the stellar wind torque relative to the formulation of Matt & Pudritz (2008a) adopted here.

Much work remains to develop the necessary theory, to improve the precision and number of observational measurements of relevant system parameters, and ultimately to understand the observed distributions and evolution of stellar spin rates, but the idea that powerful stellar winds may extract significant angular momentum from accreting stars remains a promising scenario.

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